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Quota-based carbon tracing model for construction processes in China

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ABSTRACT

Carbon emissions contribute substantially to climate change. Many researchers believe that the construction industry can contribute significantly to carbon dioxide reduction through cleaner and more sustainable building production and construction, e.g. low energy building design and the use of low carbon materials. Nonetheless, the environmental impacts associated with construction process should not be underestimated. Despite that, as construction process is complex and involves many participants, the calculation of carbon emissions during the construction process is never an easy task. Divergence and limitation are found in both the system boundary and carbon sourcing method. This research aims to resolve the problem and facilitate construction managers to identify carbon emissions so as to optimize them through better construction arrangement. In this paper, the system boundary of the construction stage is first defined and the related activities being included in the construction process are identified. A methodology of establishing the sources of carbon emissions during the construction process based on a quota-based method of China is proposed. The calculation model for carbon emissions is established according to the traditional emission factor approach with some modifications. The carbon emitted during the construction process of a case teaching building is calculated using the proposed quota-based carbon tracing (QCT) model. The QCT model not only provides a systematic framework for the tracing of carbon emissions, it could also help construction managers identify low carbon construction methods and logistics schedule in order to maximize the carbon reduction opportunity during the construction stage.

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1. Introduction

Human activities, particularly the carbon dioxide (CO_2) emitted from fossil fuel combustion, have driven the atmospheric greenhouse gas (GHG) concentration levels higher than at any time (IPCC, 2013) resulting in the warming of the earth at an alarming rate over the past century, with an average temperature increase by more than 0.8 °C per annum (1.5 °F) (NCA, 2014). In order to mitigate the effects of climate change, countries around the world have been making every endeavor to formulate relevant laws and measures to control and reduce the carbon emissions. For instance, the United States (US) has set targets to reduce GHG emissions in the range of 17% by 2020 and 26–28% by 2025 (DOE, 2016). Individual US states have taken drastic actions to reducing GHG emissions, such as California's Economy-wide Global Warming Solutions Act and the nine-state Regional Greenhouse Gas Initiative that addresses the power sector emissions in the Northeast, as well as the renewable portfolio standards in 29 states and the energy efficiency resource standards in 20 states (TWH, 2016). The European Union (EU) has undertaken to reduce its GHG emissions by 80–95% compared with 1990 by 2050. To achieve the long-term overall climate target for 2050, Germany is striving to prevent most emissions in the energy sector and energy-related emissions in the building and transport sectors, as well as in industry and business (GOG, 2016).

Most of the carbon emissions in the construction sector are originated from energy consumption. Construction building consumes a large amount of energy and generates a great deal of CO_2 (Stern, 2006). Given the volume of new buildings to be constructed due to increasing urbanization and growing population, serious effort should be attributed to make the building production process more carbon conscious and sustainable (IPCC, 2014). In order to cut down on carbon emissions, energy efficient building design and low carbon materials are introduced to the building sector (Sharrard et al., 2008). The German government's Energy Concept

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calls for a virtually climate neutral building stock by 2050 (GOG, 2016). In France, the construction of new buildings should fulfill high energy and environmental performance, and a life cycle analysis (LCA) of the environmental impacts of a building is needed to help reduce its GHG emissions (GOF, 2016). The Canadian government has decided to achieve a low-carbon future through infrastructure investments by reshaping the economy to make it consistent with the low-carbon pathways (GOC, 2016). These methods contribute greatly to the carbon reduction during the project operation stage. However, one should not ignore the carbon emitted during the construction process.

Although some researchers argued that the emissions during the construction phase are negligible, others have found that the environmental impacts associated with construction activities are underestimated (Guggemos and Horvath, 2006; Acquaye and Duffy, 2010; Wang, 2014). Based on the input-output method, Acquaye and Duffy (2010) had selected a sample of 728 Irish construction firms for analysis and found that the Irish construction sector was responsible for 13.81 mtCO_2e, comprising 2.37 mtCO_2e (17%) of direct on-site emissions, 5.39 mtCO_2e (41%) of upstream indirect domestic emissions and 5.75 mtCO_2e (42%) of upstream indirect emissions outside the region. A case study on the life cycle carbon emissions analysis was conducted by Wang (2014), which has demonstrated that the construction work was responsible for about 3% of the total carbon emissions during the project whole life stages for a rehabilitation project in China and 10% for a new building project in Australia. Although this amount is comparative less substantial, but when taking the year as the basis for comparison, the carbon emitted on site per annum has shown a rising trend. The study by Guggemos and Horvath (2006) on the construction of commercial buildings also found that when considering the complete building over its life cycle, the construction phase consumed 2% of energy and released 1% of CO_2, 7% of CO, 8% of NO_x, 8% of PM_{10} and 1% of SO_2. This is due to the dominance of the long-term use phase of 50 years compared to a relatively short construction period of around 2 years in general. Scaling up to the national level, however, the impacts of construction projects become more significant. Irrespective of whether the focus is on the whole life cycle carbon emission analysis or carbon evaluation for construction industry itself, estimating the environment impacts during the construction process is imperative.

Despite that, construction process is complex as each project is composed of many activities. Most researchers define the life cycle research scope from a macroscopic point of view (Scheuer et al., 2003; Himpe et al., 2013; Zhang and Wang, 2015). When considering the exact construction process, these studies lacked the detail and a clear definition on the sources of carbon emissions. Yan et al. (2010) summarized four major sources of emissions on construction sites, namely building materials production and transportation; energy use of construction machines; energy use for processing resources; and disposal of construction wastes. Nonetheless, as carbon embedded in building materials should have been taken into account during the manufacturing process, there is a possibility of double counting. Besides, there is no exact agreement on what kinds of logistical actions should be considered when calculating the carbon emitted on site (Cole, 1998; Guggemos, 2003; Guggemos and Horvath, 2006). The discrepancy on the research range of carbon emissions during the construction stage may affect the accuracy of carbon emission assessment in the construction industry.

Furthermore, to evaluate the environment impart of construction work on site, it requires a large volume of data, *viz*. the types and efficiency of machines deployed as well as the respective fuel and electricity consumed. According to the LCA method (ISO, 2006a; b), establishing a life cycle inventory (LCI) of the studied product is essential. Yet, this inventory does not include the data for construction work. Although several studies applied LCA to the construction phase, when it comes to evaluating the carbon emissions of construction behavior, the obstacle of data exchange between research institutes and the construction industry makes the research overly relying on other researcher's data (Chou and Yeh, 2015) or that from other countries (Wang, 2014). Researches used the available data without considering its practicality and local relevancy for carbon emission analysis. Without a credible emission data tracking and tracing method, the reliability of carbon emission analysis is questionable. Dong and Ng (2015) introduced a method of substituting local data using overseas life cycle inventories. Despite that, as construction process consists of hundreds or thousands of unit processes, collecting all the necessary site-specific data would consume considerable time and cost which renders it impracticable (Moreau et al., 2012). High-efficient technologies for evaluating the GHG emissions in the construction industry is proven to be hard to achieve.

In order to uncover the environmental impacts of the construction work on site, the research range is first defined in this paper. A quota-based carbon tracing (QCT) model is developed to estimate the carbon emissions of construction activities. Construction quota, which consists of a series information about construction activities, is used to track and trace the carbon emissions according to the detailed material and equipment consumption data. As a result, the respective carbon emissions on site can be systematically forecasted based on an emission factor approach. The calculation results would enable the adoption of carbon emissions benchmark at the bidding stage, thereby increase contractors' responsibility for carbon reduction. A case study of a teaching building project in China is presented to indicate the model assessment process and interpret the carbon emissions situation during different construction parts. The QCT model offers a more convenient, precise and efficient way for evaluating the work involved during the construction process. The model not only provides a systematic framework for tracing carbon emissions, it could also help construction managers identify low carbon construction methods and logistics schedule in order to maximize the carbon reduction opportunity during the construction stage.

2. Research background

2.1. Carbon emissions during the construction process

Currently, there is no consensus on the scope of the studies on carbon emissions during the construction process. Pacheco-Torres et al. (2014) proposed defining the scope of a building by including the materials production and building stages. The production stage includes raw material transportation and storage, material production and storage at the manufacturing plant. The building stage starts from the transportation of finished construction product from the manufacturer's warehouse to the construction site. Nonetheless, there is much argument on whether transportation outside the construction site should be taken into account in the construction process. Some researchers considered that the transportation of materials is part of construction process because the construction industry is highly dependent on imported materials (Fang and Ng, 2011; Noh et al., 2014). The energy consumption during the transportation process could take up around 20% of the industry's total (Smith et al., 2002). Therefore, the carbon emissions during that phase should be considered in the construction process (Guggemos, 2003; Guggemos and Horvath, 2006; Bribian et al., 2009). However, there are opinions suggesting that both the logistics and material production processes should be delineated from the construction process (Cole, 1998; Smith et al.,

2002; Lin and Liu, 2015). Some other researchers still cannot decide whether or not to consider the logistics process in carbon emission analysis of the construction phase (Gerilla et al., 2007; Rowangould et al., 2013), as they approached the carbon emissions from a whole project life cycle perspective.

An ambiguous system boundary will make the calculation results misleading which renders comparison among different methods impossible. Therefore, this study proposes defining the construction process by the space boundary and time boundary. With a widespread acceptance of LCA, most researchers agreed that neither materials production nor raw materials logistics process should be included in the construction process. The carbon emissions during these processes are the focus of the manufacturing cycle. However, it would be the responsibility of the construction industry if there is any unnecessary materials waste due to poor management. For this reason, this study considers that the building stage starts right after the materials are produced and ready to leave the manufacturing plant. As for the time range, the building stage is composed of two processes. First is the logistics process, which includes the transportation activities and storage on site. The second is the construction process on site when the materials and machines leave the storage yard and are used or installed on site. The carbon emissions of both the construction and logistics processes should be the contractors' responsibility. On the space range, the scope of the building stage should include the route from manufacturer's warehouse to the storage point on site (logistics process), and the route from storage point on site to the exact construction location (construction process) (Fig. 1). The reason to include the transportation on site to construction process is that this part is belonging to the second-time handling activity and is listed in the construction quota. This study focuses on the carbon tracking and tracing during the construction process. For the carbon emissions during the construction logistics process, it will be studied at a separate paper.

2.2. Carbon tracing method

It is generally agreed that there are basically two epistemic approaches to model the domestic energy consumption and the resulting CO_2 emissions (Oladokun and Odesola, 2015). According to IEA (1998), these approaches are either the top-down approach or the bottom-up approach. Some researchers developed calculation paradigms based on both the top-down and bottom-up approaches in order to achieve a more robust model (Crawford et al., 2010; Kavgic et al., 2010; Kelly, 2011; Chang et al., 2012).

The perspective of the top-down modeling approach is quite different from that of the bottom-up approach as it starts with aggregated data and the data is then disaggregated as far as possible to provide a comprehensive model (Oladokun and Odesola, 2015). An input-output method is one of the top-down approaches. It is based on the records of the source of input and the destination of output for a government department during a certain period. Mathematical model is built according to the energy consumption analysis and the forecast of the effects on economic activities (Hawdon and Pearson, 1995; Su et al., 2010). In the absence of any micro data, the input-output approach is an effective method for carbon emission assessment (Sandanayake et al., 2016). This method has been applied at different stages of the whole building life cycle, such as materials preparation, construction process, operation stage, etc. (Seo and Hwang, 2001; Chen and Zhang, 2010; Su et al., 2010; Chen et al., 2011). Yet, as the input-output approach uses the average emission data of an organization, it does not provide a detailed analysis on every single process, and this could result in a large uncertainty in the calculation results (Sandanayake et al., 2016). Johnston (2003) postulated that the top-down approach is a comprehensive approach and is therefore suitable for aiding high-level government policies and scheme decisions. However, this method lacks the flexibility and accuracy when considering the current and future technologies, and can only be used as a guide for the development of macro policy decisions (MIT, 1997). Kelly (2011) also believed that this approach does not give a reasonable consideration of the dynamic changes in environmental, social and economic direction. Since energy consumption and carbon emissions have a close relationship with technological and social phenomena, the top-down modeling approach neglects the social, technological and behavioral factors

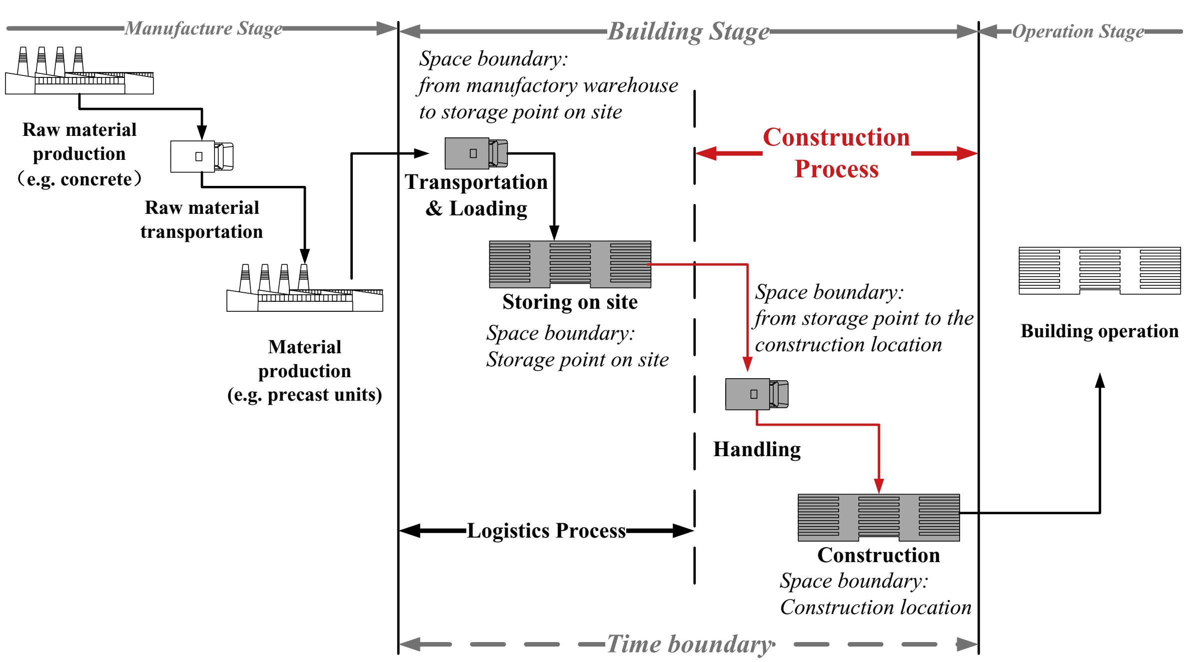

Fig. 1. Research range of carbon emissions during construction process.

making it not conducive enough to the accuracy of energy consumption and carbon emission estimation (Hitchcock, 1993). Nässén et al (2007) used the input-output analysis to calculate the energy consumption and CO_2 emissions of a Swedish construction project. The results were then compared with a bottom-up lifecycle method. The results show that the input-output method is around 90% higher than that of the life cycle method.

In contrast, the bottom-up approach begins with a set of highly disaggregated carbon emission data of each part of a building and ends by aggregating them up as far as possible to derive the whole carbon emissions of a building (Shorrock and Dunster, 1997; Johnston, 2003). The commonly used bottom-up approach is generally based on study of the work process, including a real-time measurement method, material balance method or emission factor method. The real-time measurement method is a statistical calculation method by monitoring and measuring the flow velocity, flow rate and concentration of the gas through continuous measurement facilities, and subsequently calculating the total carbon emissions based on the measured data (Filippin, 2000). The real-time measurement method requires the representativeness and preciseness of selected samples. Once this requirement cannot be met, the data monitoring will lose its significance. In addition, the cost of this method is relatively high. The material balance algorithm complies with the mass conservation law. It is based on the idea of energy flowing into the system being equal to the energy flowing out of the system. It is a scientific measurement method to quantitatively analyze the use of materials in the production process. Although this method is adopted in lots of carbon emission estimations, it needs to track and trace the input and output of the whole project life cycle in order to calculate the carbon emission of a building. The process is, therefore, very complex (Acquaye and Duffy, 2010).

The emission factor method is a method to calculate the value of carbon emissions according to the amount of average gas emissions for per unit of energy consumption under normal economic and technical management conditions. The emission factor method can be regarded as a simplified method of the material balance algorithm (Gustavsson et al., 2010). This method is based on the process, and it needs very high quality data support. The emission factor method has been used in some research on carbon emissions during the construction stage (Li et al., 2010; Kua and Wong, 2012; Rossi et al., 2012). However, due to the variety of construction processes, the use of the emission factor method requires an accurate basis of active data sources and reasonable emission coefficient of resource consumption. As the data exchange between the industry and research institutes is not easy, most researchers choose to use second-hand data and make revision to the exist database based on certain assumptions. These calculation results should be carefully evaluated. In order to overcome the limitation of using the emission factor methods, this study proposes a quota-based carbon tracing method to solicit a detailed list of activity data during the construction process. This method can be regarded as a bottom-up approach. Although the calculation of carbon emissions is based on traditional emission factor methods, the quota-based carbon tracing can help obtain actual and detailed resource consumption data during the construction process.

3. Model development

3.1. Model structure

Some countries around the world including China have been applying a quota system to managing a construction project especially during the bidding and construction stages. These construction quotas are primarily established by the contractors or consultants according to their historical records and experience. There are also some associations in the construction industry which help prepare the quota for small and medium enterprises, despite the form may be slightly different. The construction quota in China is published by the government with the information provided by contractors. The general resource consumption which is recorded in the construction quota from the government is open to public and easy to collect. Because of that, it makes carbon tracking and tracing easier than in other countries.

At the bidding stage, the owner decides a benchmark for the project's carbon emissions with the QCT model. The carbon emissions of each potential bidder cannot go beyond this level or it will fail in the bid. This benchmark is calculated according to the bill of quantities (BQ) and the construction quota published by the government or consultants which reflects the general construction productivity level in the society. When the contract is awarded, it is the contractor's responsibility to supervise the real-time carbon emissions during the construction stage to prevent the actual carbon emissions exceeding the benchmark established in the contract. The real-time carbon emissions can be calculated based on the quota of the contractor and the exact working quantities of construction activities. The calculation results can be compared with the carbon emission benchmark from time to time to ensure an effective carbon emission control during the construction stage. The ultimate carbon emissions would be evaluated at the completion stage. Methods to reduce carbon emissions in future can also be identified.

Fig. 2 describes the typical carbon tracing process based on the QCT model. Irrespective of which stage carbon emissions is going to be evaluated, the construction quota can offer the level of consumption of machines, materials and labors for all possible construction activities. As the carbon emissions of materials will always be considered by the manufacturing industry, this study will not be focusing on that part of carbon emissions. When the wastage at the construction stage is high, e.g. extra carbon emissions could have been emitted as a result of rework or poor management, the contractor will be responsible for offsetting the carbon emissions of such additional materials. As for the carbon emissions arising from the labor, some researchers proposed that it should be estimated and added to the construction process. However, this study assumes that the extra carbon emissions of labor activities should be quite minimal and can therefore be ignored. Instead, the use of machines as a main source of energy consumption is accompanied to carbon emissions. As a result, the respective carbon emissions due to the use of fossil fuel and electricity should be identified and accounted for according to the resource consumption information. The total carbon emissions can be calculated using the emission factor method. Basically, there are five steps in the QCT approach, i.e.:

(1) Select and aggregate the resource consumptions (machines in this study) of construction activities according to the BQ and the quota;
(2) Gather the energy consumption data (fossil and electricity) of the resources;
(3) Find and modify the emission factor of energy according to project situation;
(4) Summarize and compare the carbon emissions of different parts during the construction process; and
(5) Give suggestions on carbon reduction methods.

3.2. Model description

The QCT model is built based on the worksheets of construction

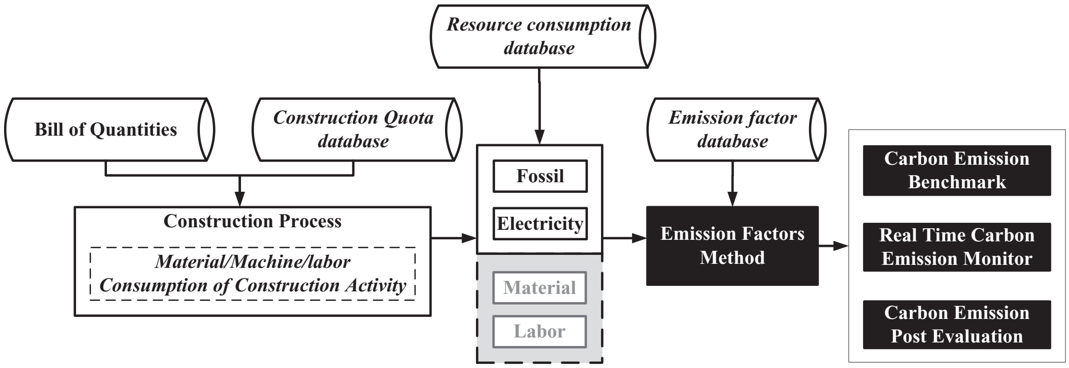

Fig. 2. Model structure of quota based carbon tracing process.

quotas, energy consumption and emission factors. The data comes from the government, consultants or contractors. Construction quota worksheets record the resource consumption quantities of construction activities for one unit of construction work. Table 1 is parts of the construction quota worksheet from the Chinese government. It records the resource consumption of foundation excavation. The differences among quota no. A1-22, A1-23 and A1-24 are the types of soil to be excavated. Different types of soil will consume different amount of resources (labor, material and machine) for the excavation work. Take quota A1-22 as an example, to excavate 1000 m^3 of foundation (trench/pit) would require a crawler excavator with single bucket to operate for 2.730 machine days (md, with 1 machine day = 8 machine hours) and a crawler dozer to operate for about 0.273 md. When combined with the project's BQ, the sum of resource consumption of the project can be determined.

Energy consumption worksheets stores the fossil or electricity consumption of 1 construction machine working for about 8 h (1 md). Take crawler excavator with single bucket (hydraulic pressure, bucket capacity = 1 m^3) for example, the code of crawler excavator in Table 1 is 9901031. According to this code, the energy consumption can be found in the energy consumption worksheet (Table 2). It needs 63 kg of diesel oil when working for 1 machine day.

The emission factor worksheet records the carbon emission quantities for each unit of energy consumption. There are many studies offering the emission factors of fuel and electricity consumption, such as Intergovernmental Panel on Climate Change (IPCC), World Resources Institute (WRI), U.S. Energy Administration (EIA), and U.S. Environmental Protection Agency (EPA). As the case study in this research is located in the south of China, the emission factors published by the GDRC (Guangdong Development and Reform Commission) of China (2017) are adopted with some modifications. Table 3 lists the emission factor of fossil and electrical kinds of energy (EF_{Fossil} & $EF_{Electricity}$) in the energy consumption worksheet. NCV_m is the net calorific value, i.e. the calorific value for the unit energy consumption. CC_m is the coal content for unit calorific value. When carbon is oxidized into CO_2, the molecular weight will change from 12 to 44. The modification to the previous research is that the carbon oxidation rate (OF) of fuel is considered in the emission factor calculation function which is always assumed to be 100% by previous research (IPCC, 2006). Although the OF most liquid fuel is about 98%, or even 99%, when the emission quantity is huge, the deviation will make the results inaccurate. Therefore, the EF_{Fossil} based on the calorific value and weight can be calculated according to equations (1) and (2) (IPCC, 2006).

$$EF_{Fossil} based\ \ on\ \ calorific\ \ value = CC_m \times OF \times \frac{44}{12} \tag{1}$$

$$EF_{Fossil} based\ \ on\ \ weight = CC_m \times OF \times NCV_m \times \frac{44}{12} \tag{2}$$

There is no record for the emission factor of firewood. As this kind of resource is seldom used during construction, it will not affect the calculation results. Besides, as the case project is located at the south of China, the electricity is supplied by the China Southern Power Grid. The emission factor of electricity is according to the data published by the Department of Climate Change, National Development and Reform Commission (NDRC) of China (2014).

In order to estimate the total consumption of energy *i* during the construction process (q_i), the work quantities of equipment (WQ_j) shall be collected from the construction quota worksheet along with the project's BQ. The respective consumption of energy *i* (EC_{ij}) should be aggregated based on the energy consumption worksheet. The total consumption of energy *i* by all equipment is summarized according to equation (3):

$$q_i = \sum_{j=1}^{m} WQ_j \times EC_{ij} \tag{3}$$

The total carbon emission during the construction process E_{CO2} is based on equation (4), where EF_i represents the carbon emission

Table 1
Construction quota worksheet 1.

Quota Code			A1-22	A1-23	A1-24
Quota Name (Unit of measurement: 1,000m^3)			Dig foundation (trench/pit) with excavator		
Resource Code	Resource Name	Unit	Soil 1 & 2	Soil 3	Soil 4
9901031	Crawler excavator with single bucket (Hydraulic pressure, Bucket capacity = 1m^3)	md	2.730	3.040	3.360
9907016	Crawler dozer (75kw)	md	0.273	0.304	0.336

Note: The classification of soil is according to "Soil and rock classification table" in "National unified construction quota" of China.

Table 2
Energy consumption worksheet for construction machine.

Resource Code		9901001	9901011	9901021	9901031	9901041
Energy	Resource Name	Crawler excavator with single bucket (Hydraulic pressure)				
	Bucket capacity (m^3)	0.3	0.6	0.8	1	1.25
	Unit	1 machine day				
gasoline	kg					
diesel oil	kg	54.00	33.68	50.23	63.00	78.24
Coal	kg					
Electricity	kWh					
Water	m^3					
Firewood	kg					

Table 3
Emission factors worksheet.

Energy	Unit	NCV_m (MJ/t)	CC_m (g/MJ)	OF	EF_{Fossil} based on calorific value (g-CO_2/MJ)	EF_{Fossil} based on weight (kgCO_2/kg, kgCO_2/kwh)
Gasoline	t	43,070	18.90	98%	67.914	2.925
Diesel oil	t	42,652	20.20	98%	72.585	3.096
Coal	t	20,908	26.37	89.63%	85.776	1.796
Firewood	–	–	–	–	–	–
Electricity	kwh	–	–	–	–	0.596

factor of energy i.

$$E_{CO2} = \sum_{i=1}^{n} EF_i \times q_i \tag{4}$$

4. Case study

4.1. Data collection and calculation

In order to introduce the work and analytical process of the QCT model, a study case is selected. The case project is a 4-story high teaching building. The construction area is 2189.29 m^2. It took about 1 year to construct and it was finished in 2016. There were about 12 divisional works during the construction process. With the work breakdown method, the works can be separated into stages, and then activities. To complete each divisional work, construction activities would occur during different stages of the divisional work. In order to provide a clear idea about the QCT method for the construction process, this research selects three construction stages during the earthwork to introduce the calculation method. They are foundation excavation, backfilling, and transportation of excavated materials off-site. Related construction activities are taken out during each of the construction stages.

Table 5 is the BQ for the earthwork, and A1-22, A1-9, A1-147 and A1-25 are the activities' quota codes. According to these codes, the consumption of materials, machines and labors can be found from the construction quota worksheet. As only the carbon emissions of machines are considered in this study, for earthwork of the teaching building, the per unit work quantity for construction machines of A1-22, A1-25 and A1-147 are gathered from the construction quota worksheet (Tables 1, 6 and 7).

According to the construction quota, four machines namely crawler excavator (CE), crawler dozer (CD), dump truck (DT), and electric rammer (ER) were used during the earthwork stage of this project. When the unit consumption of the machines is multiplied with the work quantities in the BQ, the workload of construction machines can be achieved as summarized in Table 8.

According to the resource code of CD, CE, ER and DT in Table 8, the fossil and electricity consumptions during the earthwork stage can be derived in the energy consumption worksheet (4^{th}-6th column in Table 9). The carbon emissions of each machine can be calculated with the respective emission factor based on the weighting in the emission factor worksheet (7th and 8th columns in Table 9). As a result, the total carbon emissions of the four machines during the earthwork stage is worked out as 2008.51 kgCO_2.

Fig. 3 compares the carbon emissions of the four machines during the earthwork stage. The CE and ER discharge more CO_2 than the other two machines. The reason is that the unit energy consumption of CE and the workload of ER are a little higher. These two machines should be the focus of energy saving.

4.2. Results and analysis

Based on the QCT approach, the carbon emissions of the whole project can be calculated. The results show that about 34 kinds of machines are needed during the construction process and the total carbon emissions of the project amount to 7726.32 kgCO_2. The unit carbon emissions are 3.53 kgCO_2/m^2. The carbon emissions of electricity are about 61.52% of total carbon emissions because 28 kinds of machines are electricity driven. The top ten machines with most carbon emissions are listed in Table 10 and a comparison can be found in Fig. 4. The carbon emissions of these machines take up 91.95% of the total emissions. Most of carbon emissions come from the electrical hoist and trucks (48.61%), which are all belonging to

Table 5
Bill of quantities for earthwork.

Construction stage	Quota Code	Activities	Units	Quantity
Foundation excavation	A1-22	Excavate foundation (trench/pit) with excavator (Soil 1&2)	m^3	1035.75
	A1-9	Excavate foundation (groove/pit) by labor (Soil 1&2, $\le$2 m)		
Backfilling	A1-147	Backfilling, tamping with rammer	m^3	1216.51
Transportation of excavated materials	A1-25	Digging soil with excavator, transporting soil with dump truck (Soil 1&2, $\le$5 km)	m^3	173.00

Table 6
Construction quota worksheet 2.

Quota Code			A1-25	A1-26	A1-27	A1-28
Quota Name (Unit of measurement: 1000 m^3)			Excavating soil with excavator transporting soil with dump truck			
			within 1 km			increased 1 km
Resource Code	Resource Name	Unit	Soil 1&2	Soil 3	Soil 4	
9901031	Crawler excavator with single bucket (Hydraulic pressure, Bucket capacity = 1m^3)	md	1.860	2.110	2.690	–
9907016	Crawler dozer (75kw)	md	0.420	0.494	0.599	–
9907261	Dump truck (8t)	md	10.940	13.020	14.840	2.640

Table 7
Construction quota worksheet 3.

Quota Code			A1-144	A1-145	A1-146	A1-147
Quota Name (Unit of measurement: 100m^3)			Backfilling			
			Loose filled	Manual ramming	Tamping with rammer	
Resource Code	Resource Name	Unit			Flat ground	Trench/pit
9913161	Electric rammer (20-62kNm)	md	–		5.530	7.180

Table 8
Work quantity of construction machines for earthwork.

Quota Code	Resource Code	Resource Name	Unit consumption	BQ (m^3)	Work quantity (md)
A1-22	9901031	Crawler excavator with single bucket (CE) (Hydraulic pressure, Bucket capacity = 1m^3)	2.73md/1,000m^3	1035.75	2.83
	9907016	Crawler dozer (CD)(75kw)	0.273 md/1,000m^3	1035.75	0.28
A1-147	9913161	Electric rammer (ER)(20-62kNm)	7.18 md/100m^3	1216.51	87.35
A1-25	9901031	Crawler excavator with single bucket (CE) Hydraulic pressure, Bucket capacity = 1m^3)	1.86 md/1,000m^3	173.00	0.32
	9907016	Crawler dozer (CD) (75kw)	0.42 md/1,000m^3	173.00	0.07
	9907261	Dump truck (DT) (8t)	21.50 md/1,000m^3	173.00	3.72

Table 9
Carbon emission for earthwork.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Resource Code	Resource Name	Work quantity (md)	Energy	Unit consumption	Energy consumption	Emission Factor	Carbon Emissions ($kgCO_2$)
9907016	CD	0.35	Diesel oil	53.99 kg/md	18.90 kg	3.096 $kgCO_2$/kg	58.50
9901031	CE	3.15	Diesel oil	63.00 kg/md	198.45 kg	3.096 $kgCO_2$/kg	614.40
9913161	ER	87.35	Electricity	16.60 kwh/md	1450.01 kwh	0.596 $kgCO_2$/kwh	864.21
9907261	DT	3.72	Diesel oil	40.93 kg/md	152.26 kg	3.096 $kgCO_2$eq/kg	471.40
					Total Carbon Emission		2008.51

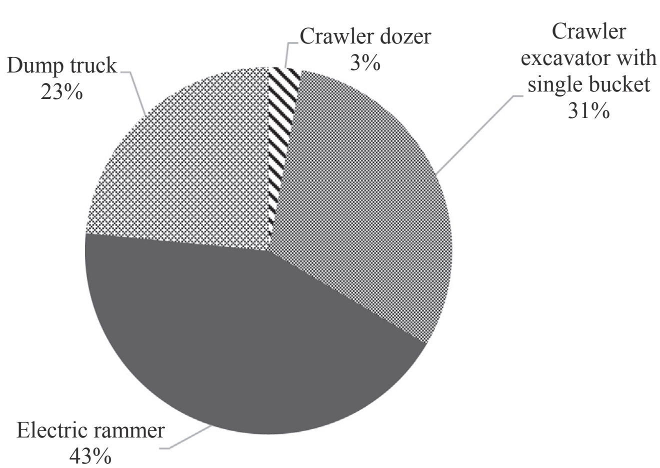

Fig. 3. Carbon emissions comparison of machines during earthwork.

the measurement work. The measurement work mainly includes the activities for construction technology and organization, such as the transportation of scaffolding and molds on site (horizontally and vertically). Trucks are used for the transportation of scaffolding and molds on site and a certain range of off-site transportation. Electrical hoist is used for vertical transportation within 20 m. Therefore, it can be concluded that the carbon emissions for vertical transportation and a certain range of off-site transportation account for a large proportion of total carbon emissions. The construction logistics process cannot be neglected if contractors wish to minimize the carbon emissions during the construction stage.

The carbon emissions among the divisional works are shown in Fig. 5. The carbon emissions of 6 of the divisional works have already taken up 99.98% of total carbon emissions during the construction process, while the measurement work, earthwork and steel work account for 94.32% of total carbon emissions.

4.3. Validation and discussion

The QCT model has been applied to evaluate the carbon emitted during the construction process of a subsea tunnel project with super large diameter shield method in Zhuhai, China (Dong, 2016).

Table 10
Carbon emissions of top ten machines during construction process.

Name of Machine	Construction process	Abbreviation	Carbon Emission ($kgCO_2$-eq)	Percentage
Electric hoist (10 KN)	Measurement work	EH-10	1979.61	25.62%
Truck-6t	Measurement work	T-6	1776.03	22.99%
Electric rammer	Earthwork	ER	864.16	11.18%
Crawler excavator with single bucket	Earthwork	CE	614.26	7.95%
AC electric welder	Steel work	ACE	476.53	6.17%
Dump truck	Earthwork	DT	471.38	6.10%
Concrete pump (extra)	Measurement work	CP	332.58	4.30%
Argon (arc) welder	Railing work	AW	280.45	3.63%
Butt welder	Steel work	BW	167.92	2.17%
Steel bending machine	Steel work	SB	142.00	1.84%
		sum	7104.92	91.95%

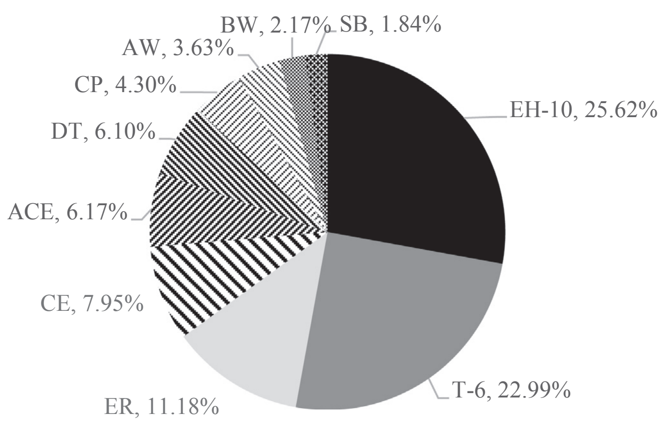

Fig. 4. Carbon emission of machines for the whole project.

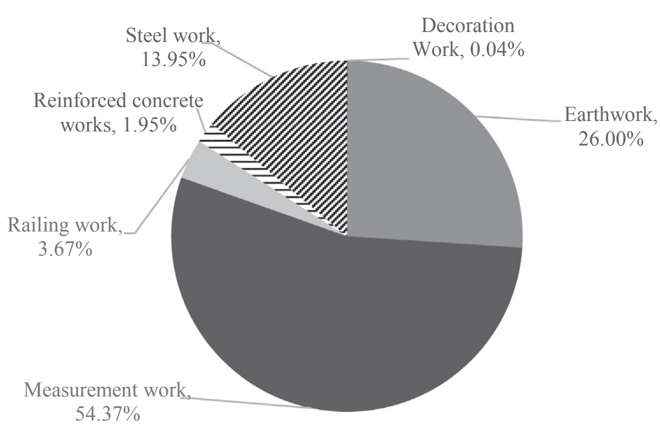

Fig. 5. Carbon emission of divisional works.

The tunnel is 2.8 km long which is divided and separated into three sections, i.e. the south bank section, shield section and north bank section. The construction quota was originated from contractor's experience. The missing data was collected by the researchers through site visit. The carbon emissions of the three sections mentioned above are 10,485.42 tCO_2, 55,337.67 tCO_2 and 3.77 tCO_2 respectively. The unit carbon emissions are 23.51 tCO_2/m^2. Suggestions were provided according to the carbon emissions of the different construction parts and machines. The project was appraised to be of international standard of green technologies and carbon reduction methods by experts in China. When comparing with the case project, it can be found that the carbon emissions of the tunnel project is much higher than that of the case project. While the construction method and unit of accounting are different, the construction scale of these two projects are greatly different. The investment of the tunnel project is about 1458 times more than that of the case project. More construction works and large size machines with more electricity were used in the tunnel project. The result is also compared with two commercial buildings based on the life cycle method (Wang et al., 2016), and the unit carbon emissions for the buildings in China were 1.183 tCO_2/m^2 while that in Australian were 0.28 tCO_2/m^2 which are indeed closer to the case project. These two buildings had the highest level of rating under their national green evaluation standard, with the unit carbon emissions lower than those of the case project. When compared with the QCT method and the construction component of most life cycle methods, QCT offers a more convenient, precise and efficient way for evaluating the carbon emissions arising from work during the construction process.

The government of China is interested in using the QCT model for forecasting the carbon emissions of other public projects. As carbon trading in China is in its infancy, mainly focusing on the manufacturing industries like steel, electrical, chemical, and building materials, the private owners and contractors in the construction industry are not particularly active on their environmental responsibility. Through the site visits and interviews with contractors, owners and consultancies, it is found that most private owners and contractors are more concerned about the cost of carbon evaluation, especially as there is no carbon trading in the construction industry to allow private companies to reap the benefits brought by carbon reduction. In contrast, public organizations are more interested in carbon evaluation as this is an environmental commitment of the government. When the carbon trading market in China covers all the construction industry, it is expected that private companies will do more carbon evaluation to achieve the benefits of carbon reduction in construction projects.

Interviews were also carried out with experts and consultants who have international experience. They generally believed that the QCT method is cost and time effective to exercise, and the model can be adopted by other countries because both contractors and consultants have their own construction quota databases which are based on historic data and experience though suitable adjustment to the form of system database should be carried out. They also opined that the obstacle for improving carbon evaluation during the construction stage in most advanced countries is that the construction scale is not as big as those in China and other developing countries. The carbon evaluation during the construction stage is not attractive both for the mandatory emission reduction markets and the spontaneous trading markets, as these countries are more concerned about the selection of building materials. However, some experts claimed that more attention should be attributed to carbon emitted during the construction stage as more countries are interested in the Belt and Road Initiative of

China, and it will lead a large volume of construction works in China and other the countries along the Belt and Road Initiative.

5. Conclusions

Many studies have been conducted on the carbon emissions of the construction industry, but most of these studies focus on the carbon emissions during the building operation stage. As building construction is always divided into many different phases while many participants are involved in the construction process, the calculation of carbon emissions during the construction process remains rather difficult. There are two important problems during the study of carbon emissions at the construction stage. First is to define the system scope and decide the time and space boundaries of the construction process. The second is to identify a method for tracing the carbon emissions arising from the activities. Although various methods of calculating the carbon emissions during the building operation stage have been proposed, these methods cannot be easily used at the construction stage. Previous studies focusing on the embodied GHG emissions of buildings were restricted by limited system boundaries due to a lack of details in the off-site process data. The calculation of carbon emissions during construction process would require a more practical database.

In this study, an analytical and calculation tool namely the QCT model has been developed and introduced to estimate the environmental performance of the building construction process. The construction quota database of China is used to provide a baseline for consumption information of machines, materials and labors for various construction activities. As the carbon emissions of materials is considered by the manufacturer, this study does not focus on that part of the carbon emissions. Besides, this study ignores the carbon emissions arising from labor activities. Therefore, the main source of carbon emissions is accompanied with the use of machines. With the fossil and electrical consumption data of construction machines and their respective emission factors, the carbon emissions during the construction process can be calculated.

A case study located in South of China has been conducted to illustrate the QCT method. It is found that the carbon emissions for vertical transportation and a certain range of on/off-site transportation contribute most to the environmental impact of building construction. Therefore, more attention should be attributed to the construction logistics strategy to reduce the carbon emissions during the construction stage. The carbon emissions of the studied project account for 3.53 $kgCO_2/m^2$, with 61.52% coming from electricity consumption. This estimation result can be used as a benchmark during the bidding stage. As the quota adopted in the case study is published by the government, it reflects the general construction level of technology and management. When the contractor is submitting their bidding documents, they should apply and state their own enterprise's quota. If the carbon emissions estimated by the contractors is above the benchmark, they should make every endeavor to cut down on the carbon emissions. Otherwise, they may be declined to enter the bidding stage.

This research proposes a scientific methodology which can be used in practice. It also offers a fair benchmark for the evaluation of low carbon construction solutions. Furthermore, the outcomes of this study should provide an important foundation for future research. The construction quota in China is a static carbon tracing method which is based on history data. It can be used as a forecasting tool. When the project enters into construction stage, the contractor plays a key role in balancing the construction schedule, transportation mode and inventory. The management behavior of contractor would have great influence on the carbon emissions during the actual construction process. Dynamic research is needed to help construction managers supervise and optimize the carbon emissions. Therefore, based on the carbon tracing model in this study, future research on the development of a more robust dynamic model to meet the requirements by considering the human behavior on carbon emissions during the construction process should be developed. Besides, the logistics activity should be carefully considered in future studies.

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